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Microgravity monitoring at the Miravalles geothermal field - some preliminary results

Hallinan, S.E., Brown, G.C. and Rymer, H.

Dept. of Earth Sciences, The Open University, Milton Keynes, England.

Abstract

Eight deep wells have been drilled into intra-calderic lavas and pyroclastics to the southwest of Miravalles volcano; Guanacaste, Costa Rica. These intersect a liquid dominate^ geothermal aquifer below 800m with a maximum temperature of 257 C. The aquifer is apparently structurally not stratigraphically bounded and the permeability is dominantly secondary, due to fracturing of the host rocks. The field is due to go into production in the early 1990's.

Under static conditions (i.e. when the wells are closed) no significant microgravity differences (33(iGal at the 68% confidence level) were observed between surveys in March 1987 and January 1988. Five microgravity surveys from January to March 1988 also revealed no significant changes. During a five day well testing period in late March 1988, when 126,000 tonnes of water were produced from 4 wells, gravity increases were observed following well closure. These were studied in detail using 4 LaCoste and Romberg gravity meters (G.105, G.513, G.840 and D.61). Measurements revealed a sharp increase of 30-40 |J.Gal within 10 minutes of well closure and a further rise of 30-60 (iGal over the next week, levelling off to pre-testing values. These changes have been modelled in terms of pressure-related expansions of the steam zone base within the aquifer and of depressions in the shallower water table associated with production. Neither model is entirely satisfactory because rapid movement of very large masses of water (10"-10' tonnes to cause the gravity changes observed) is probably unrealistic. These experiences however, will allow a more useful experiment to be designed for the next and longer 5 month well testing period beginning in late 1988.

Introduction

The Miravalles geothermal field is located within the 10km Guayabo caldera, Guanacaste, Costa Rica (Figure 1). The Costa Rican electricity board, Instituto Costarricense de Electricidad (ICE), plan to operate a 2x55 MW power station there in the early 1990's and to date 8 deep wells have been drilled.

The caldera collapse structure shown in Figure 1 (<600,000 years old; ELC.1986) is well exposed as andesitic lava scarps in the western sector but the more recent resurgent cone, Volcan Miravalles, has obscured the eastern side. The southern margin has been disected by the N-S trending La Fortuna graben. The intra-calderic geology has been ascertained from borehole information and geophysical modelling and a N-S cross-section is shown in Figure 2. The oldest unit penetrated by drilling, the Ignimbrite Unit, is thought to lie above an andesitic basement and is made up of at least 860 m (well 15) of welded tuffs.The Lava-Tuff Unit is restricted to wells 1, 5, 10 and 15 and is made up of andesitic/dacitic lavas alternating with crystalline and lithic tuffs in a 2:1 ratio. The overlying Volcano-Sedimentary Unit is ubiquitous and made up of a 500-1000m sequence of tuffs, lavas and lacustrine deposits laid down between the contemporaneous lava domes of the Dacite-Latite Unit. The domes are of limited lateral extent but up to 940m thick under wells 2, 5, 10 and 11. Both latter units are capped by the Cabro Muco Andesite Unit made up of 120-360m of andesitic lava flows. This unit is replaced by the possibly contemporaneous 300m thick Pumice Unit at well 15. The uppermost Post Cabro Muco Volcanic Unit, made up of recent lavas, tephras, lahars and lacustrine deposits, forms the present topography.

Subsurface structure, namely faults apparently bounding blocks of different geothermal significance, has largely been deduced from geoelectric data (Duprat and Leandro, 1986). The dominant structural control on geothermal fluid flow is the series of N-S faults related to the La Fortuna graben (Figure 1). The E-W Hornillas Fault is the main conduit feeding the fumaroles between wells 2, 3, 5 and 11. It is difficult to assess permeability within the buried aquifer as the above units are heterogeneous and permeability is largely fracture induced, not primary. Permeability, highest in the Volcano-Sedimentary Unit, increases to the south at well 12, but decreases to the west at well 15.

The 8 deep wells were drilled to delineate a high temperature (up to 257 °C) liquid-dominated geothermal aquifer. The principal zones of production are deeper than 800m and most lie within the Volcano-Sedimentary Unit. The isotherms from N-S and E-W profiles shown in Figure 3 suggest a deep heat source north of well 11.

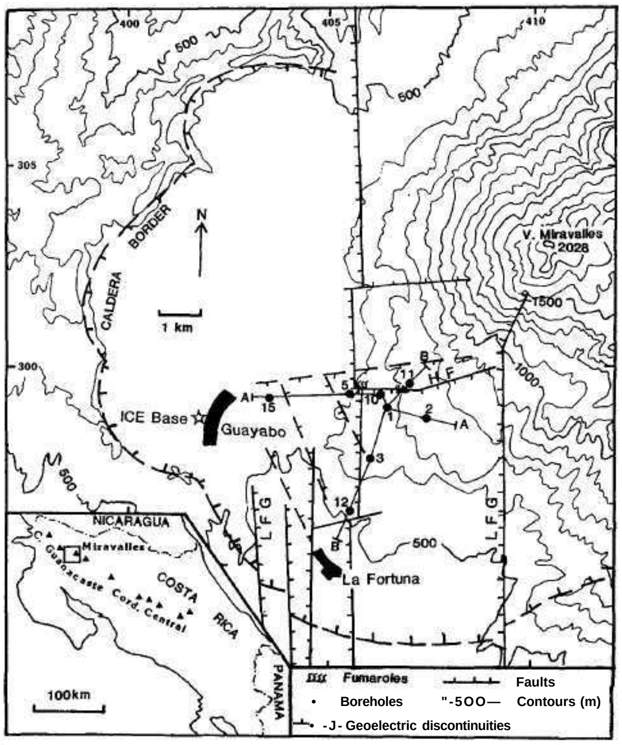

Figure 1: The Miravalles geothermal field. Showing the boreholes and the main structural features (after ELC, 1986). LFG = La Fortuna graben; HF = Hornillas fault; A-A, B-B = profiles through the geothermal field (cf. Figures 2 & 3).

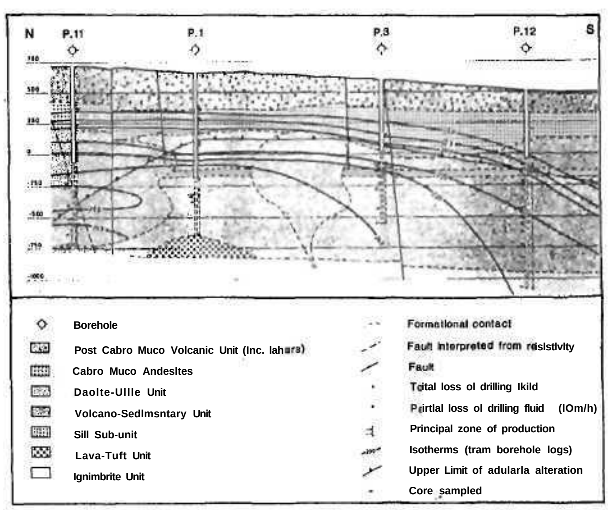

Figure 2: Geological section B-B (after ELC, 1986). The presence of the central Dacite-Latite body has been deduced from geoelectric data (Duprat and Leandro, 1986). Vertical scale (m) = horizontal scale.

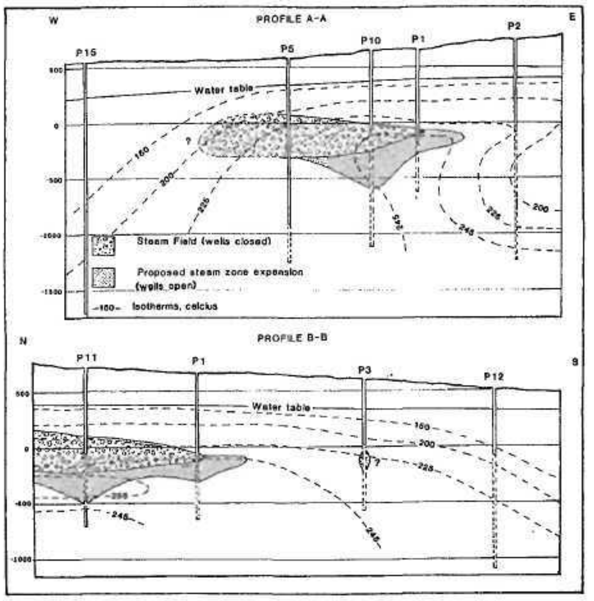

Figure 3: Geothermal field profiles A-A and B-B. These profiles show the proposed steam zone during normal conditions (i.e. wells closed) and the proposed steam zone expansion during production. The extent of this latter zone has been modelled from gravity observations during testing only of wells 1,10,11 and 12.

Microgravity monitoring

During 1985-6 ICE reported large microgravity changes (up to lmGal) around wells 1, 2, 10 and 11 using a Worden gravity meter. The Open University conducted two microgravity surveys in early 1987 and five more from January to March 1988, over the same stations, using more accurate LaCoste and Romberg meters and using proceedure adopted by Rymer and Brown (1984 and 1987) for monitoring Poas volcano. A base station was chosen outside the geothermal field at Guayabo (Figure 1). Spacing between ICE gravity stations around wells 1, 2, 10 and 11 (Figure 4) was sufficiently close to allow modelling of any possible gravity changes due to mass changes below the top of this part of the aquifer (> 800m below surface level). Each survey was conducted in one day, during which the field base (either station 362, 502-D or P.I 1) was cross-looped at least every five readings. Only one field base station was used in each survey and this was tied back three times daily to the Guayabo base station.

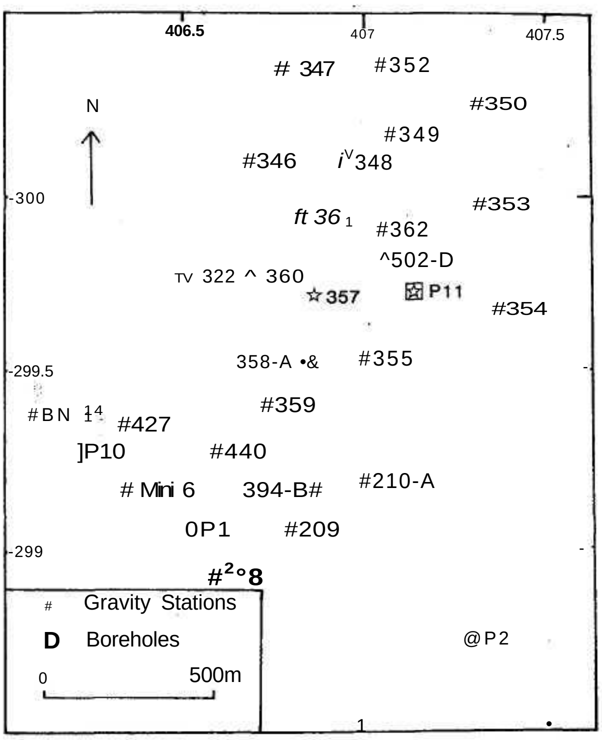

Figure 4: Microgravity stations near wells 1, 2, 10 and 11. Includes gravity stations repeatedly measured during the early 1987 and 1988 field seasons.

Cross-looping allowed the instrumental mechanical instabilities (tares) to be assessed and eliminated using the proceedure described in detail by Rymer, 1988. After correcting for Earth Tides (predicted using the programme of Brouke et al., 1972) each reading was expressed as a difference from the mean reading at the Guayabo base station for that day. No significant changes were observed between surveys (33|iGal at the 68% confidence level; Rymer, 1988).

Microelevation surveys over the same stations were conducted, using an EDM theodolite, in early 1987 and in both January and March 1988. No significant elevation changes were observed between these surveys. A 10cm elevation change corresponds to a gravity change of c. 20|iGal; standard Bouger-corrected free air gradient, assuming an average rock density of 2.6Mg irT^3.

Observations related to well tests

Wells 1, 10, 11 and 12 were opened from 18-23 March 1988. Due to adverse weather conditions during this period, microgravity readings were imprecise and unreliable. Results did not show significantly different values from the period prior to well opening. Before the wells were closed it was concluded that any gravity changes associated with geothermal production over this timescale were likely to be below the limit of detection for normal microgravity survey techniques. Accordingly it was decided to eliminate the errors incurred when the instrument is moved by monitoring gravity close to the wells continuously during the well closure period. From previous experience this reduces the standard deviation to 10|iGal (at the 68% confidence level) which is further reduced to ca. 7|iGal when two adjacent meters are used simultaneously. Successive closures of wells 10,11 and 12 were monitored in this way.

In each case observations made over a 20-30 minute period bracketing well closure, at positions within 2m of the well head, show a related increase in gravity. The results for this period shown in Table 1 are statistically highly significant (>7|iGal at the 68% confidence level) with good agreement between the different meters used at each site. The results for well 11 are shown graphically in Figure 5. The master graph shows data collected at the surface level of the concrete pit surrounding the wellhead (lower graph), a hut 20m to the east and (with two instruments) 80cm below ground level in the pit. Values on the y-axis are differences from the Guayabo base station. The 0.3% calibration difference known to exist between instruments G.105 and G.513 does not affect the mean increase during well closure. The detailed information for this critical period appears as an inset to Figure 5. The data show the rapid increase upon well closure (within 10 minutes) and in the case of wells 10, 11 and 12 there were significant (>33|iGal at the 68% confidence level) increases following the initial sharp rise, resulting in total gravity increases of 77, 61 and 94|iGal respectively, to values similar to those recorded before well testing. Reliable microelevation data recorded at wells 1 and 10 during the well testing period and immediately afterwards showed no significant elevation changes (< 4cm).

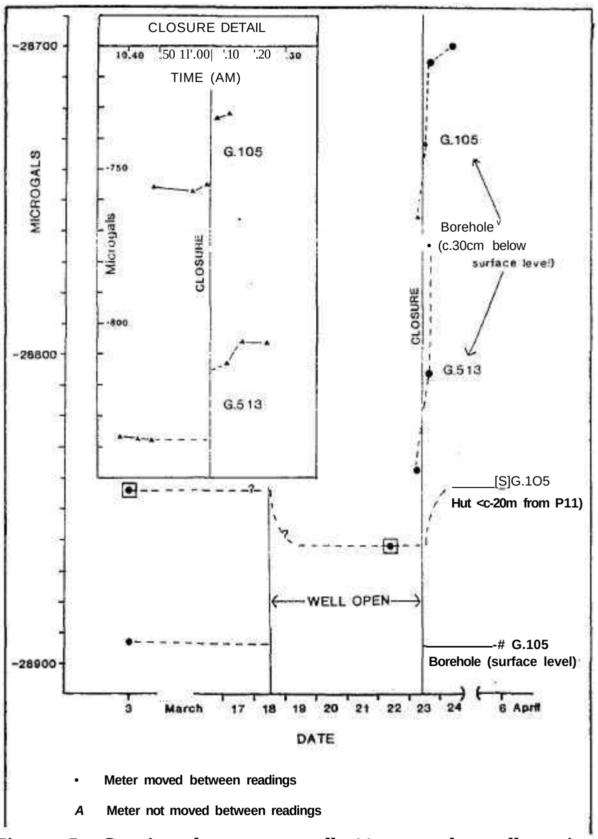

Figure 5: Gravity changes at well 11 over the well testing period, March 1988. Inset shows detail of the sharp gravity increase during the hour covering well closure. Gravity values are differences in |iGal from the Guayabo base station (Figure 1). The hut is a station 20 m east of well 11.

	17th March	22	23rd (AM)	23rd (AM)	23rd (PM)	24th	5 th April	INCREASE AT CLOSURE	LONG PERIOD TOTAL INCREASE
		<——OPEN——>							
PI									
G105 (Hole)	-20136	-	-	-	-	-	-20149	-	-
G105 (Hut)	-	-20187	-20176	-	-20144	-20143	-	-	+ 32
G513 (Hut)	-	-	(-20071?)	-	-20140	-	-	-	-
D-61 (?)	-	-	-	-	-19885	-19940	-	-	(+55)
									32
P10									
G105 (Platform)	-16820	-16856	-16856	-16840	-16812	-16812	-16786	+ 16	+ 70
G513 (Platform)	-	-	-17882	-17832	-17790	-	-	+ 50	+ 92
D-61 (Step)	-	-	-17607	-17555	-17538	-	-	+ 52	+ 69
							Average	39(3)	77(3)
							"n-1	20	13
P11									
G105 (Hut)	(-28863?)	-28862	-	-	-	-	-28841	-	+ 21close
G105 (Platform)	-28903*	-	-	-	-	-	-28905	-	-
G105 (Step)	-	-	-28756	-28732	-28706	-28700	-	+ 24	+ 56
G513 (Step)	-	-	-28838	-28806	-28765	-	-	+ 32	+ 73
G840 (Hut)	-28882	-28918	-	-	-	-	-	-	- 36(opening)
G840 (Step)	-	-	-28651	-28611	-28596	-	-	+40	+ 55
D-61 (Hut)	-	-	-	-	-28935	-28886	-	-	(+49)
• = read on 3rd March						Hole	Average	+ 32(3)	61(3)
G105 reading on 3rd March at the Hut was -28843							°n-1	8	10
						Hut	Average	-	28(2)
							°n-1	-	10
P12									
G105 (Platform)	12672	-	-	-	-	-	12664	-	-
G105 (Step)	-	-	12875	12915	12905	12964	-	+ 40	+ 89
G513 (Platfoim)	-	-	12705	12739	-	-	-	+ 34	-
G840 (Platform)	-	-	12697	12739	12796	-	-	+ 42	+ 99
D-61 (Step)	-	-	-	-	12972	12987	-	-	-
D-61 (Platfoim)	12614	-	-	-	-	-	-	-	-
							Average	39(3)	94(2)
							"n-l	4	7

Table 1: Gravity changes at wells 1, 10, 11 and 12 over the **period of well testing. Values** recorded as differences in uGal from the Guayabo base station. Values in parentheses were not included in the calculations. The hut is a station 20m to the east of well 11.

Interpretation of well closure gravity increases

The following discussion addresses the question of mass increases upon well closure and this is modelled initially as being due to the rapid influx of water as the steam condenses beneath the observation site. (Condensation within the cased volume of the well accounts for less than 4(j.Gal). The starting point is data on the pressure-temperature variations in each well, observed by ICE engineers prior to well tests, which are plotted in relation to the vapour-pressure curve for pure water (Kennedy and Holser, 1966) in Figure 6a. The marked kink in each curve represents the point where the aquifer is reached and conditions become almost isothermal (probably due to hydrothermal convection) while pressure continues to increase with depth. Although the field is generally assumed to be water-dominated, P-T paths for wells 1, 10 and 11 intersect the vapour- pressure curve for water and steam zones of limited vertical extent will occur adjacent to these wells. However, there is no steam field suggested by the well 12 data due to the lower temperatures and higher pressures in this southern area. Figure 3 shows N-S and E-W profiles through the geothermal field (assuming that well P-T conditions are typical of aquifer conditions). For conditions pertaining during well tests the net reduction of pressure both down and adjacent to each well has been measured at the surface and estimated at depth. This pressure reduction, shown in Figure 6b, increases the volume of the aquifer lying within the steam field.

The two constraints now available viz.(i) the incremental depth range over which the steam zone is likely to form and (ii) the magnitude of the gravity reduction, hence mass change, were used to calculate the additional volumes of the steam zone produced when the wells are open (assuming mass increases only due to condensation and inflow of water). Necessary assumptions in these calculations were a typical aquifer porosity of 10% and that the incremental steam volumes take die form of downwards tapering cones (broadly representative of the probably asymptotically curved steam expansion body shown in Figure 7). The gravity effect along the axis of a buried inverted cone, g^^, was calculated by integrating the gravity effects of incremental cross-sectional discs of the cone over the length of the cone.

$$g_{cone} = 2\pi G\Delta\rho\Big(h + \cos a\{(a^2\cos^2 \alpha + h^2\sin^2 a)^{1/2} - b\cos a \ldots + b\sin^2 a[\sinh^{-1}\tfrac{C\_2a\_ - \tan a)}{b\sin 2a} - \sinh^{-1}\cot a]\}\Big) \quad (1)$$

where G=the gravitional constant

Ap=the density change (O.lMg m'3)
a=the depth to the top of the cone
b=the depth to the base of the cone
h=the height of the cone
a=the cone half-angle (refer to Figure 7)

Equation (1) above satisfies the limiting conditions: that as either a or h tends to zero, or a tends to infinity; g_{mne} tends to zero.

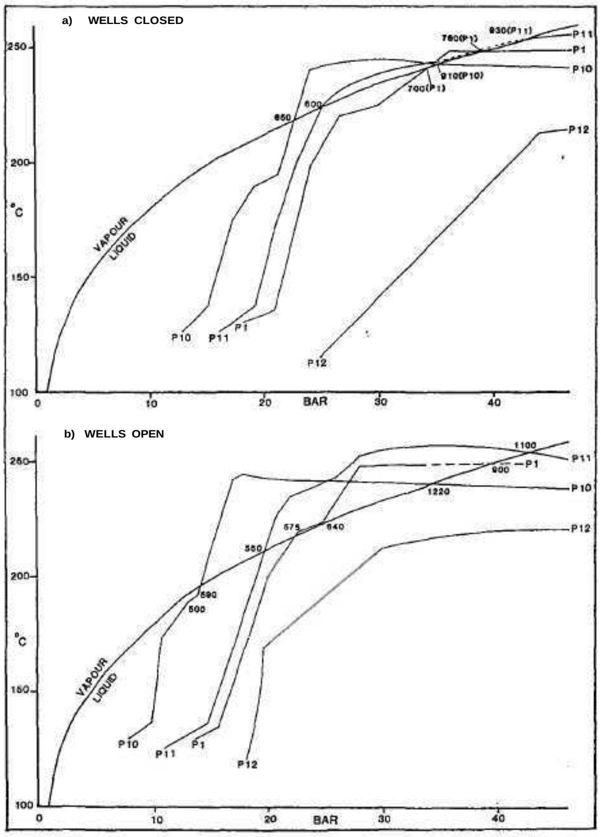

Figure 6: Pressure-Temperature graphs **for** wells 1, 10, 11 and 12. Down borehole depths (m) to the steam-water interfaces are shown at the intersections of the graphs with the boiling curve for water (Kennedy and Holser, 1966). Note the effect of a pressure drop (b) is to expand the steam zone.

A useful approximation given that a, the unknown, is difficult to separate from (1) (a determines the volume of the cone) is to let the entire mass of the cone act from its centre of mass (CM in Figure 7). Then the cone radius, r (which varies with a) is given by:

$$r = x\left(\frac{3Ag}{JiGhAp}\right)^{1/2} \ldots\ldots (2)$$

where x is the depth to the centre of mass, x=l/4(3a+b), and Ag is the observed gravity change due to the steam zone expansion. Table 2 summarises the results and shows the mass changes calculated for the respective gravity change at each well. Using the cone half-angles calculated indirectly from (2) and substituting them into (1) (together with the respective values of a and b) to calculate g_{cone}, it is possible to gauge the degree of approximation (re. the mass of the cone acting from CM) introduced into (1). For wells 1, 10 and 11; g_{cone} = 28, 65 and 48^Gal respectively. This means that the masses calculated from (2) are underestimated by 12-15%, considered to be within an error margin reasonable for this experiment.

The calculated mass changes in Table 2 are very large and cause for concern. It is physically unreasonable to move upwards of 3,000,000 tonnes of water into each steam zone, almost instantaneously, upon well closure. Moreover, the total mass of water discharged from all the wells was only 128,000 tonnes (data from ICE). Thus, the steam zone expansion model implies that the steam-water interface is forced out (i.e. downwards and sideways) into the aquifer during production. This is difficult to reconcile with the fact that pressure drops during production. A further problem, given the ICE P-T data, is the absence of a steam zóne at the well 12 site (Figures 3 and 6).

Unfortunately, due to adverse weather conditions, there are insufficent data to produce a microgravity profile to enable the depth and lateral extent of the associated mass changes to be constrained. One alternative shallower site of mass change might be a saucer-like depression in the water table in the region of the well (Figure 8) associated with the drop in steam zone pressure during production. The saucer also approximates to a cone and calculations are similar to above. (Note, however, that the approximation to a point source is less realistic here as the depth to the water table is less than to the base of the steam zone). Results presented in Table 3 show how for a given observed gravity change the postulated mass change increases with x, the depth to the centre of mass change. Although smaller, the required mass changes at shallow depths are still considered to be unreasonably large. Clearly more data must be collected over a wider distribution of points so that gravity changes observed during well testing can be contoured and the source depth estimated more accurately.

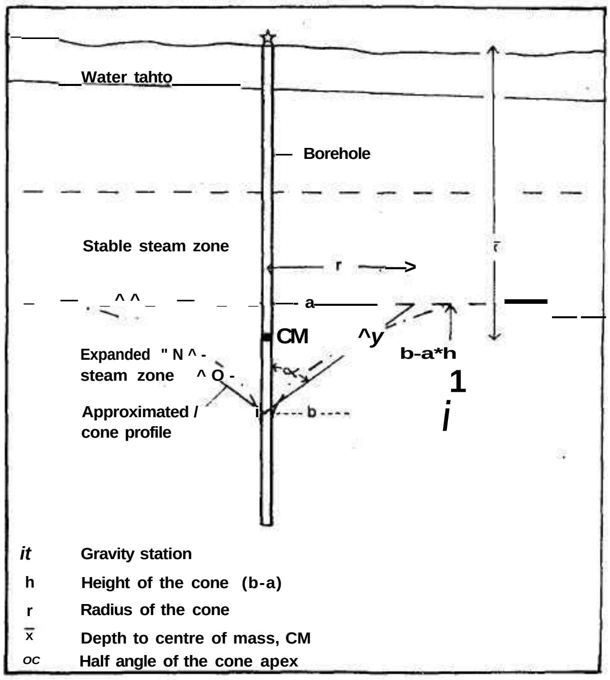

Figure 7: Steam cone model. This shows the approximation of the probably asymptotically curved steam expansion body to a cone and also shows the parameters used in equations (1) and (2) (see text).

Will	•<m)	b(m)	7(m)	40' (liGal.)	4M' (kg)	t'(m)	u '	(MGala)	4M (kg)	r M	a	(H«al)
1	760	900	795	-	-	-	-	32	3xK>9	455	73°	28
10	810	1220	987	39	S.7xio9	418	53°	77	11 X109	586	62°	65
11	930	1100	972	32	4.5 X10^9	505	71°	61	9x109	697	76"	48
12	-	-	-	39	-	-	-	94	-	-	-	-

Table 2: Mass changes calculated for the steam zone expansion model. AM[1], p' and a' are values calculated for the rapid rise (within 10 minutes) in gravity upon well closure, Ag'. AM, p and **a** are values correspondingto the total increase in gravity, Ag after well closure. Scone- snown for comparison, is calculated from equation (1) using parameters from this table (see text). The radius, r is used to constrain the steam expansion zone in Figure 3. See Figure 7 for nomenclature.

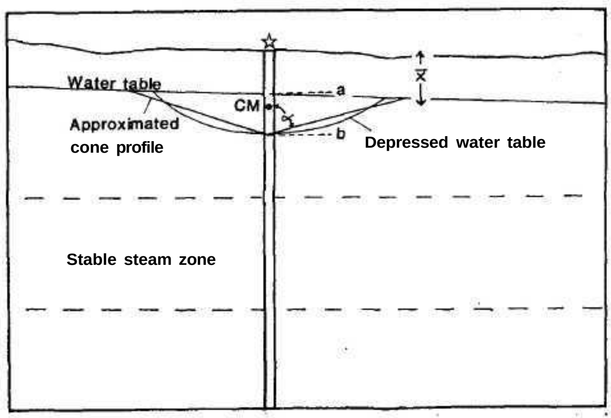

Figure 8: Depressed water table model. Notation as for Figure 7.

				«- - - - Vary? _ ______-*			
Well	Ag ftiGals)	Depth to Water Table (m)	AM (kg) (b-a=100m)	AM (kg) (x = ioom)	AM (kg) (Sf = 400m)	AM (kg) (if = 700m)	SZE model AM (kg)
1	32	301	5x 10^e	0.48 x 10»	7.7x108	23 X10^8	30 x 108
10	77	288	11	1.1	18	56	110
11	61	344	12	0.9	14	45	90
12	94	193	6	1.4	22	69	-

Table 3: Mass changes calculated for the water table depression model. Mass changes for the steam zone expansion (S.Z.E.) model and for other values of x, the depth to the centre of mass, are shown for comparision. Ag is fixed as observed.

Conclusions and future objectives

Microgravity monitoring of the Miravalles geothermal field during production is viable. There can be no doubt that rapid increases in gravity were observed (up to 40|iGal), at the wellhead, upon closure of the wells, following five days of production. The observations were significant because of the low margin of experimental error (c. 7^Gal), achieved by using more than one gravity meter and by not moving the meters between readings.

The observations made at Miravalles are however, paradoxical. Aquifer pressure drops during production in the vicinity of the well and as the water flashes into steam the steam zone expands into the aquifer. But the mass of water required to move into this zone, within 10 minutes of well closure, to cause the gravity increase observed is over 100 times the mass of water discharged at the surface during testing. This imbalance, coupled with the anomaly of an observed increase in gravity at well 12 where there is apparently no steam zone, means that the steam zone expansion model is impractical. Similarly the water table depression model is inadequate because again the mass of water involved is unreasonably large.
The most critical element missing from the modelling process is the ability to derive the depth to the source of the observed gravity change. A five month production (from well 11) and reinjection (into well 2) test, beginning in December 1988, should provide adequate time to build up a reliable microgravity variation profile across the wells. Assuming sufficient gravity changes can be observed (>a worst case reader error of 33|iGal), this profile will enable the depth to the mass change to be estimated and a more constrained model to be formulated. Readings will be taken repeatedly before, during and following testing at fixed points along the profile. Spacing of the stations will be denser in the vicinity of the wells but expanded towards the edge of the field to minimise the total number of stations and thus maximise the number of repeat readings possible in a given survey. Microelevation surveys will be carried out to check for possible elevation changes associated with production.

If this method proves applicable, then it would be possible to use the microgravity monitoring technique in the pre-production phase of geothermal field assessment as well as in its well documented use during production (Allis and Hunt, 1986; Hunt, 1987; Atkinson and Pedersen, 1988).

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